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Production, Transmission and Detection of Cherenkov Light in Oil

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Contents

Abstract

The information required to describe the production, transmission and detection of Cherenkov light in the MiniBooNE mineral oil is available in sufficient detail to allow one to describe the important features. We will calculate the spectrum of photons which create the photoelectrons by which we detect the Cherenkov signal in MiniBooNE. The photoelectron yield *vs.* wavelength of the light is determined for various pathlengths of light. A peak near 400 nm for light passing through 10 m of oil shifts to about 390 nm for 5 m and nearer 360 nm for 1 m light path length. Integrals of these curves predict the photoelectron yield per centimeter of path for a relativistic particle. This yield is suitably characterized by two exponentials, one with the attenuation length characteristic of the 390 nm light which is most common and another much shorter attenuation length component for light which is absorbed in the first 1-2 m from the production point.

1 Introduction

We will begin with the theoretical Cherenkov production spectrum, a simple characterization of the light attenuation with an attenuation length which increases linearly from near zero at 310 nm to 27 m attenuation length at 500 nm, and a quantum efficiency curve for the phototubes from the MiniBooNE BooMC Monte Carlo documentation. A simple spreadsheet calculation then provides predictions for the yield *vs.* wavelength. (As is customary, we characterize the light by the vacuum wavelength.)

We will identify the sources of information and their limitations and describe the results. Can we now deduce the properties of use so that we can characterize how well these input properties will need to be determined? This memo is a preliminary result which should be followed by a more complete TN in which the details are more completely reviewed and the errors are evaluated.

2 Cherenkov Effect

The production of Cherenkov light is described by Jackson p 498, equation (14.133). In my 1962 edition (using cgs units), the radiated energy per unit frequency interval per unit path length is

$$\frac{dI(\omega)}{dx} = \frac{e^2\omega}{c^2}[1 - \frac{1}{\beta^2\epsilon(\omega)}] \tag{1}$$

We convert to the number of photons by dividing by $\hbar\omega$

$$\frac{dN(\omega)}{dx} = \frac{e^2}{\hbar c^2}[1 - \frac{1}{\beta^2 \epsilon(\omega)}] \tag{2}$$

and integrating this [while neglecting the dependence of ϵ on ω], we have photons in an interval from ω_1 to ω_2 given by

$$\frac{dN}{dx} = \frac{e^2}{\hbar c^2}[1 - \frac{1}{\beta^2 \epsilon(\omega)}][\omega_2 - \omega_1] \tag{3}$$

We note that $\epsilon(\omega) = n^2(\omega)$ and $\alpha = \frac{e^2}{\hbar c^2} \sim \frac{1}{137}$ so that converting to (vacuum) wavelength in place of frequency we have

$$\frac{dN}{dx} = 2\pi\alpha[\frac{1}{\lambda_2} - \frac{1}{\lambda_1}][1 - \frac{1}{\beta^2 n^2(\lambda)}] \tag{4}$$

This is the number of photons per centimeter of path in the interval from λ_1 to λ_2 where the wavelengths are the vacuum wavelength of the light measured in centimeters. If the Cherenkov angle is Θ_C then $\sin^2\Theta_C = [1 - \frac{1}{\beta^2 n^2(\lambda)}]$. We have a coefficient, $2\pi\alpha[\frac{1}{\lambda_2} - \frac{1}{\lambda_1}]$ which depends upon the wavelength interval. In the memo by G. T. Garvey revised on December 18, 2003, he uses 500 visible photons. An interval from 340 nm to 540 nm yields 499.46 in my spreadsheet calculation. We will move on to integrate over the phototube sensitivity and the light transmission in the oil but for reference, the integral of the Cherenkov spectrum times the phototube quantum efficiency yields 94.75 photoelectrons per cm of path at production for the interval above 290 nm. The comparable number in my PDG July 2002 Particle Physics Booklet is 90 photoelectrons based on a 27% quantum efficiency.

2.1 Polarization, Integration Limits, Dispersion, and Fluorescence

The production of Cherenkov light is polarized (private communication from Byron Roe). This may become important for calculation of scattering but it is not considered in this memo.

In gaseous detectors, the integration limits for the Cherenkov light yield calculation may be limited by index of refraction considerations. There, the long wavelength limit may be set by threshold. For much of our muon range, we have $\beta \sim 1$ so the long wavelength limit is entirely set by the photocathode and oil transmission. The change in index is small.

At short wavelengths, materials often reach a resonance situation below which the dispersion is 'anomalous' and the index below 1. We do not reach that point in our measurements of the index nor of the oil transmission. The resonance pole in the pole expression fits to the index of refraction measurements is below 100 nm and our measurements do not come close to that region. We do know that below 320 nm, the light has a short attenuation length. However, the production of Cherenkov light is strong and measurements show fluorescence from the oil with excitation in the 250 - 300 nm range. In addition to the directly detected Cherenkov light, we may expect a component of isotropic light which is not from ionization (scintillation) but is rather from wave shifting of short wavelength Cherenkov light. This memo will not address this further but calls attention to this possibility.

In a dispersive medium like mineral oil, one can apply a formulation for the production of Cherenkov light which accounts for the angle variation of the light production *vs.* wavelength. We will be calculating in small bins in wavelength and will assume that this will be sufficient to account for the angle variation with wavelength.

3 Attenuation

This memo will calculate the spectrum of the detected Cherenkov light. As such, the attenuation length is relevant whereas for other issues, such as the delayed light due to scattering, we will wish to carefully separate the absorption from the scattering component. For this calculation, we will use the simple prescription for the attenuation length vs wavelength given in Figure 3b of BooNE-TN-95 (Monte Carlo Baseline). This result is described by a linear increase in the attenuation length from near zero at 310 nm to 27 m at 500 nm.

$$L_A(\lambda) = 27\frac{\lambda - 310}{500 - 310} \quad (5)$$

This is applied (without justification above 500 nm) from just above 310 nm to 650 nm. To complete the calculation, an *ad hoc* prescription is used at 310 nm and below. These arbitrary extensions of the measured results will have small impact on the calculated spectrum.

4 Index of Refraction

The index of refraction employed in this calculation is taken from Equation 1 of MiniBooNE-TN-090 by H. O. Meyer. I did not employ the temperature term (used result for 20^o C). This expression is more convenient to use in a spreadsheet than the pole expression. Differences between this expression, the pole expression and the results from the Cincinnati group [IEEE Trans. Nucl. Sci. 49 , 957 (2002)] are within a percent or so and will not affect the main conclusions of this work. The dispersion in the phase index of refraction from this formula makes changes of about 2% in the yield of Cherenkov photons.

5 Phototube Response

The spectral response of the phototube is governed by the transmittance and index match of the glass envelope and by the response function of the alkali metals used for the photocathode. For our purposes, the quantum efficiency is the useful characterization for the response.

5.1 Quantum Efficiency from BooMC Documentation

The BooMC online documentation exhibits explicitly many of the assumed properties of the detector as used in the 2003 versions of the Monte Carlo. It provides a Quantum Efficiency vs vacuum wavelength in 250 nm intervals. For this calculation, the values have been smoothly interpolated by hand.

5.2 Documented Phototube Properties

The many tubes in MiniBoone include 9-stage Hamamatsu R1408 tubes purchased for the LSND experiment and 10-stage Hamamatsu R5912 tubes purchase for MiniBooNE. The Technical Data Sheet for the R5912 is available on the web from Hamamatsu. The R1408 is no longer in production. A Technical Data Sheet which appears to have been FAXed from Hamamatsu in June 2003 has been consulted for the R1408 properties. However, it describes a 13-stage tube so a request for clarification has been sent to Hamamatsu Sales.

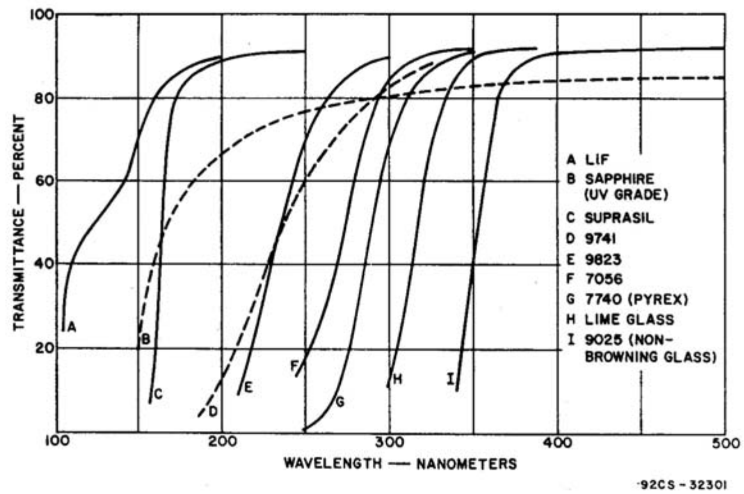

Fig. 15 - Ultraviolet transmittance cut off of various glasses and crystals used in photomultiplier photocathode windows. Data are all for 1 mm thickness.

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Figure 1: Transmittance of various phototube window materials from 1980 RCA Photomultiplier Handbook.

5.3 Transmission of Phototube Window

Light incident on the phototube surface may be reflected, transmitted or absorbed in the phototube envelope. The reflections when used in air create losses of several percent (dependent upon angle of incidence) due to the index of refraction mismatch at the surface. For oil, the index is much better matched and this loss is quite small. Care must be applied to account properly for this effect when using the typically referenced measurements of phototube properties.

The transmittance of glass for phototubes was illustrated in the RCA Phototube Manual (consider that RCA was purchased by GE in the 1980's if you doubt that this is old information). In Figure 1, we show the transmission for various phototube envelope materials. Note the curve for Pyrex. Also note that the transmission is below 100% at longer wavelengths. This is a report of the reflection losses when these windows are used in a gaseous environment.

After much searching on the internet, I find that borosilicate glass is a generic name for glass which was in the past sold only using the trademarked label, Pyrex (trademark of Corning Glass). The R1408 tubes were made with Schott 8246 Glass. Exploring using Google, one finds that this material was a special production borosilicate glass made for the SNO and LSND detectors from materials selected to have low natural radioactivity. The R5912 tubes also employ a borosilicate envelope.

Both tubes use a bialkali photocathode. With similar glass envelopes and photocathodes, one expects similar spectral responses for these two tubes. Figure 2 shows the radiant sensitivity and Quantum Efficiency for the R5912 from the on-line data sheet. On it I have plotted the Quantum Efficiency from the BooMC documentation. Figure 3 shows the same information for the (suspect) R1408 Technical Data Sheet. I know of no reason to believe that the two tubes should show different quantum efficiency. Examination of the two suggests that they are not the same but most of the difference is at long wavelengths where the efficiency is low (and the Cherenkov production is lower).

Differences between the BooMC curve and the data sheet values lie in two areas. The peak QE is higher for the BooMC curve. This may reflect a correction for the reduced reflection at the oil-glass interface due to better matching of the index of refraction. There is also a spectral cutoff at about 320 nm in the data sheet curves which may reflect the borosilicate glass transmittance. Given the Pyrex curve from RCA and the data sheet curves from Hamamatsu, it seems likely that there is a cutoff a short wavelengths which we are not correctly representing. This is a small effect but should be resolved and the correct information employed.

6 Calculated Spectral Response

Employing the inputs described above, a calculation of the photoelectron yield in response to the transmitted spectral distribution of Cherenkov light has been carried out using a spreadsheet. Employing the above model for attenuation in oil, the spectrum of photons/10 nm spectral interval/mm of particle path is calculated and plotted in Figure 4. The phototube response is then applied and the resulting photoelectron yield from each 10 nm interval is calculated and plotted in Figure 5.

At short wavelengths the useful light is limited by the transmission in oil whereas at long wavelengths it is cut off by the phototube response.

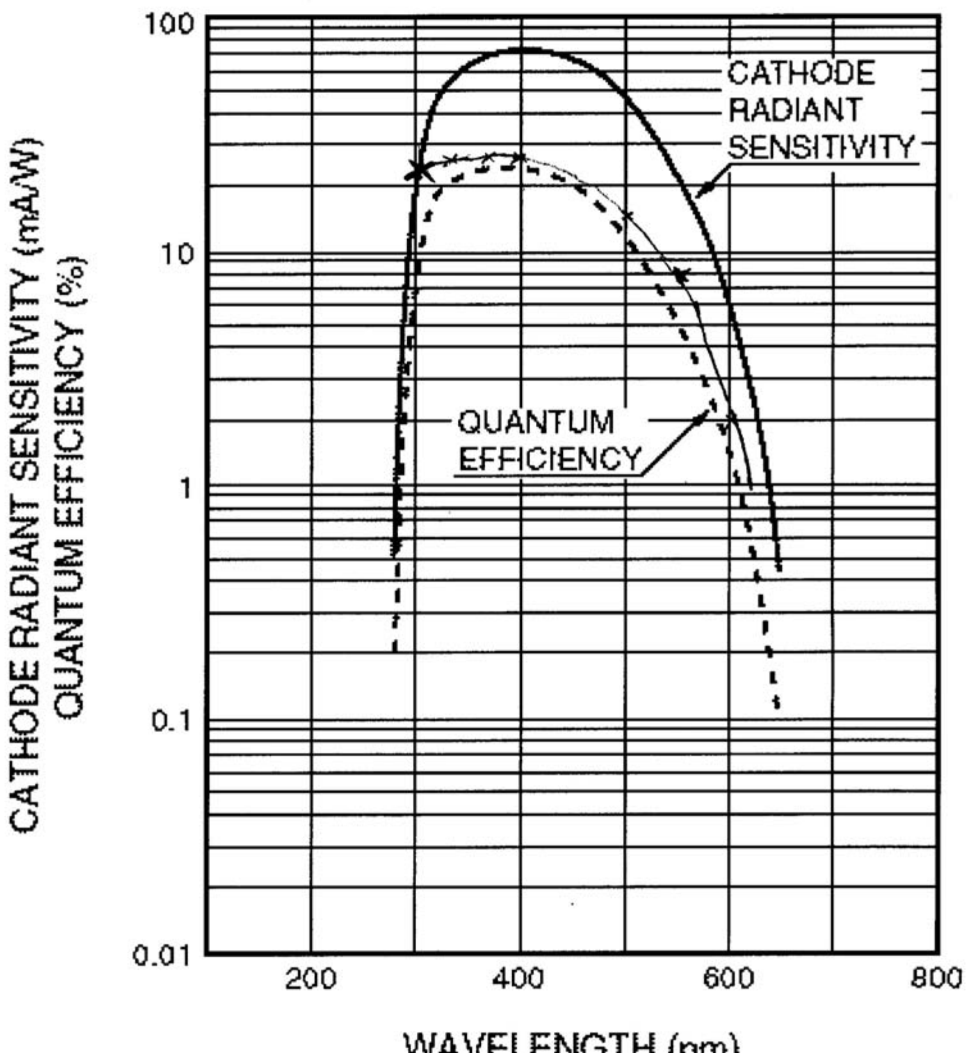

Figure 2: Spectral Response of Hamamatsu R5912 Photomultiplier Tube from Technical Data Sheet. Assumed Quantum Efficiency in MiniBooNE BooMC Monte Carlo is plotted by hand and indentified with 'x'.

This calculation suggests that the useful photons peak at about 350 - 360 nm if detected one meter from production. Photons detected 5 meters from production are most typically at 390 nm and for detection at 10 meters, the peak is at 400 nm.

Since the spectrum of light at the phototube is not recorded by the

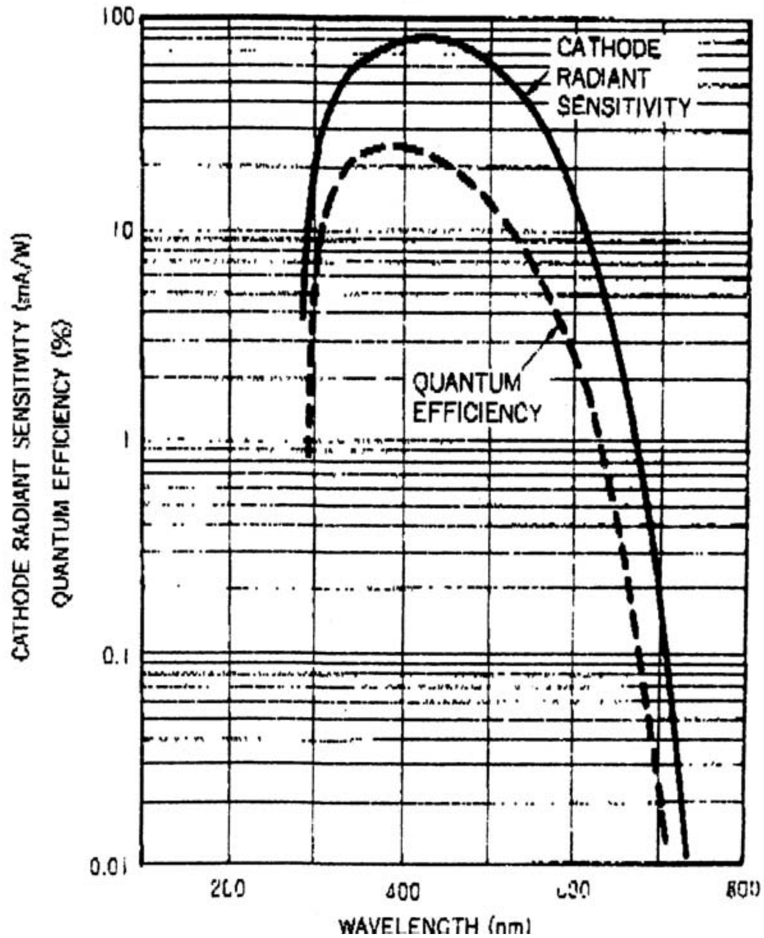

Figure 3: Spectral Response of Hamamatsu R1408 Photomultiplier Tube from Technical Data Sheet.

electronics, we next consider the integral number of photoelectrons at each distance by integrating these curves. The result is plotted in Figure 6. The result was immediately suggestive that a single attenuation curve would not describe this very well. In the spreadsheet, a calculation was added to use two exponential decays to characterize the calculated photoelectron yield. The results are shown in Table 1 with the curves plotted in Figure 6. It appears that it is sufficient to employ two exponentials with the first attenuating like the typical light of 390 nm and the other attenuating about $\times 10$ faster.

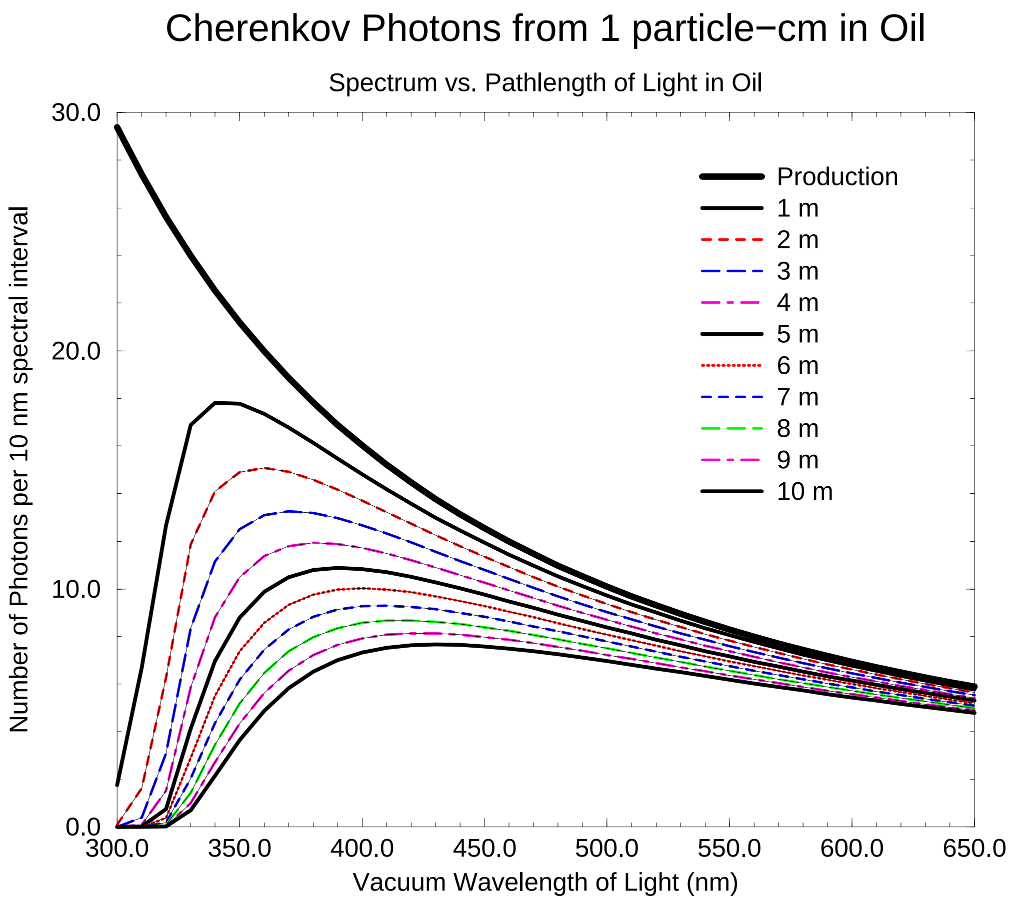

Figure 4: Cherenkov Photons produced by 1 particle-cm for $\beta = 1$ particle at production and after attenuation of 1 - 10 m of MiniBooNE Mineral Oil.

7 Observations

- Calculations which include the polarization of Cherenkov Light may be required to properly understand scattering.
- Angular differences in the produced light due to the dispersion in oil are unlikely to be important but should be considered.
- Although most of the energy emitted as Cherenkov light will be detected in the cone, some of the very short wavelength light will be ab-

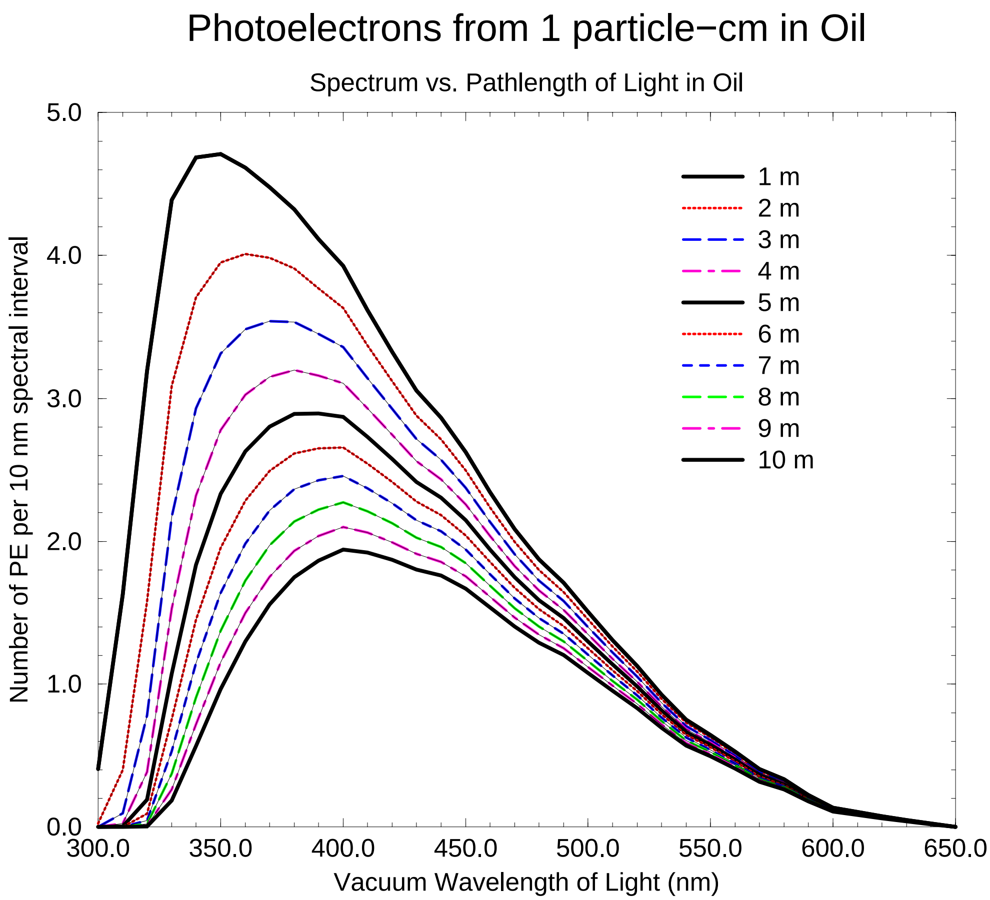

Figure 5: Photoelectrons from Cherenkov light produced by 1 particle-cm for $\beta = 1$ particle after attenuation of 1 - 10 m of MiniBooNE Mineral Oil.

sorbed and re-emitted near the source and will be distributed isotropically. We have some measurements of the spectral characteristics of this fluorescence but we need to learn if it has the 19 ns decay characteristic of the scintillation or perhaps a different (or more than one different) fluorescence lifetime. We also need to determine the fluorescence yield from this process.

- At some point we will need to review the effects of the difference between the TN-090 index of refraction and other measurements on

Component	L_A	Amplitude
	m	Photoelectrons
Main (1)	13	67
Short(2)	1.3	21

Table 1: Two Component description of Cherenkov light. These parameters describe the amplitude and attenuation length for predicting the photoelectron yield in photoelectrons per cm of path length *vs.* distance from the production point. We assume $\beta = 1$.

yield (small) and geometry (to be reviewed) and settle what values are to be used in the analysis and Monte Carlo programs. The temperature correction from 20^o C to the tank temperature should be done but variations in temperature during running are surely not significant. A future TN should document how we handle this.

8 Conclusions

- The fitting algorithms should employ an attenuation model for Cherenkov light with two attenuation lengths

$$N(x) = N_0\alpha\, e^{-(\frac{x}{L_{A1}})} + N_0(1-\alpha)e^{-(\frac{x}{L_{A2}})} \tag{6}$$

where L_{A1}, L_{A2}, α can all be fixed inputs to the fitting.

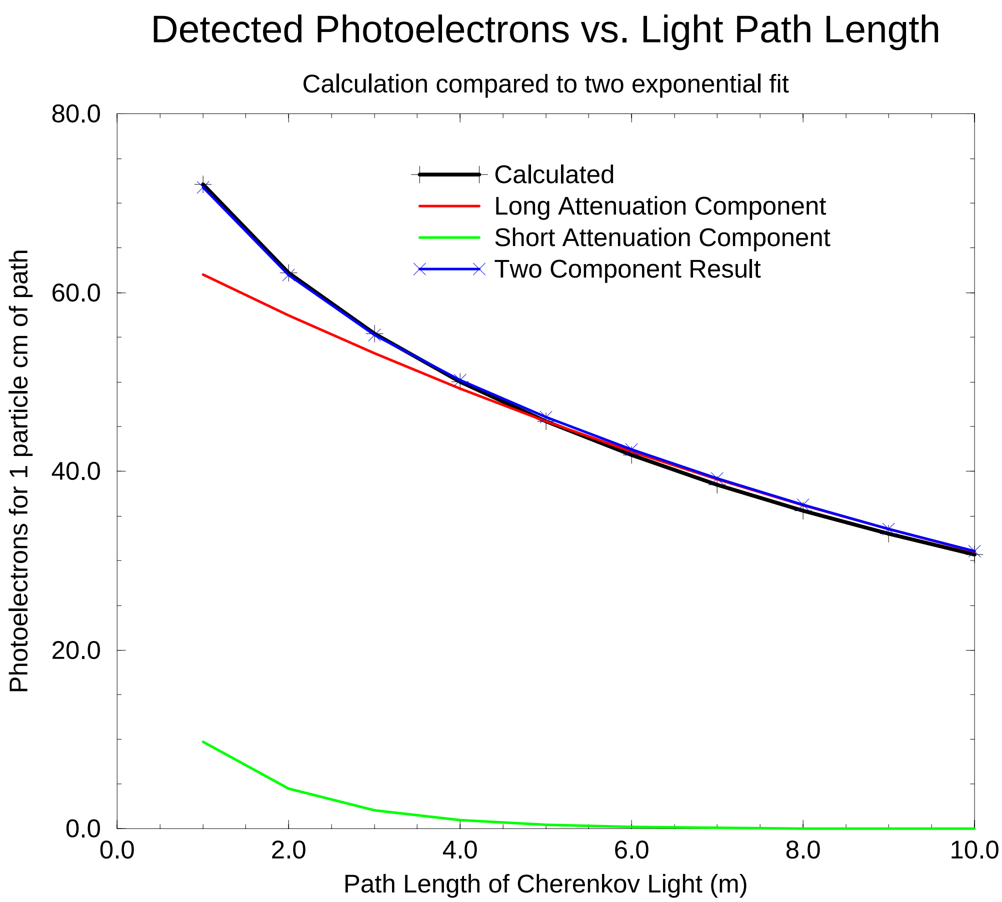

Figure 6: Photoelectrons from Cherenkov light produced by 1 particle-cm for $\beta = 1$ particle *vs* photon pathlength in MiniBooNE Mineral Oil.